Wetlands

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Matthews, E. 2000. Wetlands, in *Atmospheric Methane: Its Role in the Global Environment* (M.A.K. Khalil, ed.), pp. 202-233. Springer-Verlag, Berlin.

1. Introduction

Wetlands are most likely the largest natural source of methane to the atmosphere accounting for ~20% of the current global annual emission of ~450-550 Tg (10^{12} g) (Khalil and Rasmussen, 1983; Cicerone and Oremland, 1988; Fung et al., 1991; Crutzen, 1991; Houghton et al., 1996). Measurements of methane from Greenland and Antarctic ice cores indicate atmospheric concentrations of ~350 ppbv during the Last Glacial Maximum rising to 650 ppbv during the pre-industrial Holocene (Stauffer et al., 1988; Chappellaz et al., 1990). Pre-industrial source strengths of methane, consistent with historical concentrations and estimates based on isotopes, have been estimated at ~180-380 Tg methane annually (Khalil and Rasmussen, 1987; Stauffer et al., 1985; Chappellaz et al., 1993). Wetlands were the dominant preindustrial source with smaller contributions from wild fires, animals and oceans. During the last two hundred years, atmospheric methane concentrations have more than doubled to ~1750 ppbv (Etheridge et al., 1992). Annual increases of ~0.6% yr^{-1} in the 1980s declined to ~0.1% yr^{-1} in the 1990s (Rasmussen and Khalil, 1981; Craig and Chou, 1982; Khalil and Rasmussen, 1982, 1983, 1985; Ehhalt et al., 1983; Rasmussen and Khalil, 1984; Stauffer et al., 1985; Blake and Rowland, 1986, 1988; Pearman et al., 1986; Steele et al., 1987; Blake et al., 1988; Khalil et al., 1989; Lang et al., 1990a,b; Dlugokencky et al., 1994a,b, 1997). Currently, the total annual emission of methane is about twice that estimated for the pre-industrial period, but both the relative and absolute contribution of wetlands is smaller than in the past due to increases in anthropogenic sources and reductions in wetland areas. However, climate and related biological interactions that presently control the distribution of wetlands and their methane emissions are expected to change during the next 50 to 100 years.

The role of wetlands in the cycle of methane has been studied for several decades. Early estimates of emissions were based on very few measurements and highly uncertain information about the wetland areal extent (e.g., Koyama, 1964; Ehhalt, 1974; Ehhalt and Schmidt, 1978; Blake, 1984; Seiler, 1984; Holzapfel-Pschorn and Seiler, 1986; Seiler and Conrad, 1987). While all these studies relied on the same wetland area of 2.6 x $10^{12}m^2$ (from Twenhofel 1926, 1951), the estimated global methane emission ranged from 11 to 300 Tg/year although the more recent estimates lie in the lower half of that range. This wide range of emission figures reflects differing assumptions about the magnitude and annual duration of methane fluxes. Sebacher et al. (1986) suggested a potential wetland area of 4.5-9.0 x $10^{12}m^2$ for northern peatlands and estimated an annual methane emission from them of 45-106 Tg.

Using newer information about wetland distributions and environmental characteristics, estimates have converged around 100 Tg CH_4 yr^{-1} (Matthews and Fung, 1987; Aselmann and Crutzen, 1989; Bartlett et al., 1990) using global wetland areas of 5-6 x $10^{12}m^2$. Recent modeling studies are consistent with these values. However, the similarities mask some major uncertainties about seasonal methane-production periods as well as important differences in the relative importance of the role of climatically and ecologically distinct wetland ecosystems, i.e., tropical/ subtropical wetlands whose methane emissions are governed generally by large scale precipitation and flood cycles, and high-latitude wetlands whose highly seasonal emissions are controlled via interactions between temperature and water cycles. A complex suite of environmental parameters including soil chemistry, substrate quality and soil water status influence emissions in all these environments, further complicating the task of evaluating emissions.

Several developments in understanding the role of wetlands in the global methane cycle took place beginning in the late 1980s. Data on measured methane fluxes in wetland ecosystems expanded substantially. Measurements of concentrations and isotopic composition of atmospheric methane continued, providing more comprehensive information about sources, trends and seasonal cycles of methane. Modeling and synthesis techniques for analyzing the terrestrial and atmospheric information improved. Most recently, models of large-scale methane emissions, as well as the distribution of wetlands themselves, have made their appearance.

With respect to wetland ecosystems in particular, data expansion occurred in the following areas: (1) measurement studies increased to cover all ecosystems representative of global wetland areas (e.g., Africa, South America, Siberia); (2) periodic or single-date warm-season measurements characteristic of early field studies are augmented with measurements spanning complete growing seasons or full years in high-latitude environments (Alaska, Minnesota, Canada), measurements conducted during wet and dry seasons in tropical ecosystems (South America, Africa) and with time series of several years in Alaskan and Canadian ecosystems; (3) large-scale interdisciplinary field campaigns designed to characterize chemistry and dynamics of the regional troposphere have been conducted in Alaska, Canada, Central Africa and the Amazon Basin and integrate ground-based measurements (chambers, balloons, towers, floating platforms) with aircraft flights, and satellite overpasses. Finally, researchers have made progress toward modeling methane emissions from wetlands as well as the more difficult problem of modeling distributions of wetlands themselves.

This chapter provides an overview of the role of natural wetlands in the global cycle of methane. Table 1 summarizes aspects of wetlands important for assessing their role in the global methane cycle and indicates the complementary strengths of various approaches to understanding those features. These topics are covered in more detail in the following sections. Section 2 discusses wetland distributions and characteristics on a global scale including remote-sensing approaches to characterizing wetland extent and seasonality. Flux measurements and emission estimates at regional and global scales are discussed in Section 3. Section 4 focuses on modeling wetlands and their methane emissions. Section 5 summarizes research on assessing wetland and methane responses to climate change. The final section summarizes current understanding the role of natural wetlands in the methane budget, and outlines some remaining research questions.

Table 1.Ranking of strengths of wetland information: H = high/strong, M = medium, L = low/weak.

	Current Traditional[1]	Remote Sensing	Process Modeling	Hydrological Modeling
Area	M	H	L	M/H
Inundation Status	M	H	L/M	M
Inundation Seasonality	L	M/H	L/M	M
Vegetation Cover	H	H	L	L
Methane Flux	L/M	M	H	L
Processes	H	L	H	L

[1] includes measurements, surveys, local reports, vegetation, soil and inundation data

2. Distribution and Characteristics of Natural Wetlands

2.1 Areal Distribution and Seasonality

Early global estimates of methane emission from wetlands relied on very general information about wetland areas. Most of these estimates used a global wetland area of 2.6 x $10^{12}m^2$ put forward in the 1920s (Twenhofel, 1926). In the late 1980s, several groups have compiled data sets specifically designed to evaluate methane emissions from natural wetlands, focusing on reducing uncertainties in wetland distributions and environmental characteristics. Matthews and Fung (1987) derived a data set by integrating three global digital data bases on vegetation, ponded soils and fractional inundation at 1˚ latitude by 1˚ longitude resolution, while that of Aselmann and Crutzen (1989) was compiled at 2.5˚ resolution from regional and local wetland reports. Global wetland areas derived from these studies are 5.3 and 5.7 x $10^{12}m^2$, respectively. Relative regional distributions of areas from the two works are very similar.

About one-half of the total area lies between 50˚-70˚N. This high-latitude region is characterized by peat-rich ecosystems (bogs and fens) and a temperature-restricted thaw season resulting in highly seasonal emissions of methane. Approximately 35% of the global wetland area is broadly distributed in the latitude zone extending from 20˚N to 30˚S. This region is co-dominated by forested and nonforested swamps and marshes, with a smaller contribution from alluvial or floodplain formations. Most of these tropical wetlands, particularly floodplain habitats, undergo large seasonal expansion and contraction in response to precipitation cycles. Since many of them lie along river courses with exceptionally level topography over large distances, rapid and substantial changes in inundation during the year are common.

Differences between the two studies are discussed in Aselmann and Crutzen (1989). In brief, Aselmann and Crutzen's areas are slightly lower in the northern subtropics (10˚-30˚N), and in the southern zone between 20˚S and 40˚S which accounts for 9% of the Matthews and Fung total and 2% of the Aselmann and Crutzen total. The southern subtropical differences come primarily from the inclusion by Matthews and Fung of what are probably infrequently-flooded ephemeral wetlands in arid regions of Australia. The two studies exhibit a larger areal discrepancy in the southern tropics from the equator to 10˚S. Aselmann and Crutzen indicate that ~20% of the global total occurs in this narrow tropical zone whereas Matthews and Fung arrived at a value equal to only ~10% of the global total. Causes for these tropical discrepancies are not clear although the studies relied on different sources and compilation methodologies. A sizable portion of the locations that disagree coincide with river systems which are associated with the largest areal uncertainties.

2.2 Wetland Classification and Characterization

Both wetland data sets discussed above used simple groupings of detailed wetland information primarily because such generalizations matched the ecosystem classes represented in the methane-flux measurements available in the late 1980s. For instance, Matthews and Fung (1987) classified 28 wetland vegetation types as described in the UNESCO (1973) vegetation classification system, in addition to ~100 other vegetation types occupying locations identified as wetlands using information on ponded soils and inundation, into five major groups: forested and nonforested bog, forested and nonforested swamp, and alluvial formations. Following regional wetland classifications of the local sources used in data collection, Aselmann and Crutzen (1989) identified 45 freshwater wetland types globally which were grouped into six broad categories following Level I of the hierarchical wetland classification devised for Canada by Zoltai and Pollett (1983). To accommodate tropical environments, they added floodplains to Zoltai and Pollett's (1983) system which classes wetlands according to physiognomic features such as peat structure, vegetation cover, and inundation depth and seasonality. The resulting groups are bog, fen, swamp, marsh, floodplain, and shallow lakes. With the exception of shallow lakes, the generalized classes of Aselmann and Crutzen (1989) and Matthews and Fung (1987) are comparable.

Field measurements characterizing methane production and emission from varied wetland ecosystems over extended time periods have increased substantially since the development of these data sets. This broadening of habitat coverage now justifies using more of the information contained in the wetland data sets to either reclassify or expand the classification of methane-significant ecosystems (Gore, 1983a,b; Glaser, 1987; National Wetlands Working Group, 1988; Reeburgh et al., 1997), although this has not yet been done.

A parallel approach is advocated by Sahagian and Melack (1996) who report a new functional classification of wetlands, paralleling recent functional classifications of vegetation (Running et al., 1994; DeFries et al., 1994). The system was developed to characterize the following wetland functions (1) methane production, (2) carbon accumulation or export, (3) denitrification/N burial, and 4) sulfur cycling (DMS and H_2S production). Wetlands are therefore described with respect to the following suite of parameters most of which have been identified as controllers of methane production: (1) net primary production, (2) temperature, (3) water table and hydrology, (4) transport of organics and sediment, (5) vegetation type and morphology, (6) chemical characteristics of organic materials (lignin, N content, DOC quantity, chlorophyll), (7) salinity, (8) soil nutrient status, and (9) topography/geomorphology. This system represents a bridge between using existing data sets to characterize wetlands, modeling methane emissions from wetlands, and ultimately modeling wetlands and their response to changing climates.

2.3 Remote Sensing

Currently, the largest remaining uncertainties in estimating methane emissions from natural wetlands arise in part from difficulties in determining areal coverage of various wetland habitats, and seasonal and inter-annual variations in hydroperiod. Aselmann and Crutzen (1989) attempted to estimate maximum and minimum extent of wetland areas, and months of methane production, using hydrological and meteorological observations and wetland descriptions while Fung et al. (1991) applied a simple model based on temperature (for high latitude systems) and precipitation (for low latitude systems) to estimate seasonality and magnitude of emissions. They and others (see regional case studies included in Gore (1983b)) confirm that considerable uncertainties remain with respect to the seasonality of both areas, inundation, and emission despite the fact that the global distribution of wetlands is well understood. Seasonal expansion and contraction of tropical/subtropical swamps in response to precipitation and flood cycles is particularly difficult to estimate. For example, Bartlett et al. (1990) note that estimates of total Amazon floodplain area range over an order of magnitude and areas covered by the three main categories of Amazon floodplain habitats are poorly known. A particular problem in characterizing the areal dimension of hydroperiod is the very local variations in topography that characterize many tropical wetlands such as the Sudd, the Amazon floodplain, and the Pantanal. In contrast, the methane production season for high latitude ecosystems is regulated largely by temperature, and habitats undergo less extreme areal changes over seasons although complex terrain complicates the identification of habitats associated with different methane fluxes and controllers.

Recently, Roulet et al. (1994) and Reeburgh et al. (1997) applied measured methane fluxes for wetland environments in Canada and Alaska, respectively, to high-resolution land-cover maps of the regions derived from LANDSAT data. In these well-studied northern regions with strongly seasonal inundation periods, identification of vegetation types with distinctive CH_4 fluxes reduces uncertainties in emissions. The rationale underlying remote sensing approaches is that more precise measurements of inundation and of areal coverage of wetland habitats with different methane emission characteristics will improve extrapolation of ecosystem flux measurements to wetland habitats (Roulet et al., 1992a; Bubier et al., 1995b; Roulet et al., 1994; Reeburgh et al., 1997) (Table 1). However, remote sensing techniques employing visible and near-infrared, thermal, microwave, and radar data offer varying degrees of success in improving areal estimates of wetland habitats on seasonal and inter-annual timescales, particularly with respect to open-water and saturated-soil environments. (Refer to reviews by Hess et al. (1990), Melack et al. (1994), Morrissey et al., (1994, 1996), and Sahagian and Melack (1996)).

Early attempts to characterize wetland environments using optical satellite data (e.g., Morrissey and Ennis, 1981; Walker et al., 1982; Rose and Rosendahl, 1983; Ormsby et al., 1985; Bartlett et al., 1989) proved these data useful primarily for assessing herbaceous environments characterized by standing water, for determining extent of open water in pond-dominated northern wetlands (e.g., Hudson Bay Lowlands, Alaska), and for distinguishing wetland habitats in boreal and arctic environments albeit without determining variations in water status within soils. However, the seasonal series of LANDSAT or AVHRR data required to improve areal estimates of wetland habitats and inundated conditions are typically unattainable due to persistently cloudy conditions, especially in the tropics. Furthermore, optical instruments do not penetrate canopies, a feature that severely limits the use of these data in tree-dominated wetlands which account for about two-thirds of the world's wetlands (Matthews and Fung, 1987).

In an overview of remote sensing of lakes and floodplains in the Amazon, Melack et al. (1994) assessed data availability, spatial resolution, and classification accuracy of a series of remotely-sensed data including aerial photography, satellite-borne optical and thermal sensors, satellite-borne passive microwave sensors (e.g., Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SMM/I)), and synthetic aperture radars (SARs). They concluded that while SAR sensors are theoretically optimal for mapping inundation in the tropical Amazon because of their insensitivity to cloud cover and penetration of tree canopies, their fine resolution and narrow swaths prevent instantaneous synoptic evaluation of inundation over large areas which is a crucial element in environments with rapid and large seasonal variations. In addition, the limited wavelengths and polarizations available from currently operating SAR instruments requires combining data from several satellites to distinguish among wetland habitats, which in turn introduces problems of spatial coregistration and temporal coherence. Therefore, passive microwave instruments such as SMMR and SSM/I are likely the best suited for large-scale wetland characterization despite their coarse resolution relative to SARs.

Two passive microwave radiometers have provided global coverage since 1979. SMMR operated from 1979-1987 with 6 day global coverage and SMM/I has operated from 1987 to the present with 3-day global coverage, vertical and horizontal polarizations, and four frequencies. The highest frequencies, 37 GHz (both instruments) and 85.5 GHz (SMM/I only), offer 30 and 15 km resolution, respectively. Although SMMR provides synoptic views over large wetland regions, the coarse spatial resolution has limited its use in terrestrial studies to seasonal or inter-annual assessments (Choudhury, 1988, 1989; Giddings and Choudhury, 1989). In an attempt to minimize the problems associated with coarse resolution, Sippel et al. (1994) devised linear mixing models to incorporate observed microwave signatures of major end members into estimates of fractional inundation area.

The higher resolution, and multiple frequencies and polarizations, available from SSM/I appear more promising for assessing wetland extend particularly if combined with ancillary data for interpretation although additional problems exist (Neale et al., 1990; Achutuni et al., 1996; Prigent et al., 1997). Until recently, most land surface studies using microwave satellite observations focused on simple indices derived from linear combinations of microwave satellite measurements. However, atmospheric effects, especially cloud cover, may be responsible for a substantial part of the microwave signal, thus casting doubt on the interpretation of these indices solely in terms of surface properties (Tucker, 1989; Justice et al., 1989; Kerr and Njoku, 1993). This is particularly severe in wetland areas where clouds can persist for long periods of the year. Because flooding is typically associated with periods of heavy cloudiness and therefore maximum contamination of microwave radiances by clouds and rainfall, extreme caution is required when interpreting simple microwave indices. Even a cloud-free atmosphere can account for up to 15% of the microwave signal at 19 and 37 GHz, on average over a month, accompanied by large temporal and spatial variation (Prigent et al., 1997). Most importantly, even if cloudy conditions are avoided, and contributions of the cloud-free atmosphere are low, microwave radiation is directly influenced by variations in surface temperature making it impossible to directly compare microwave brightness temperatures over different time periods or different areas without accounting for surface temperature variations. Such effects therefore preclude direct comparisons of microwave brightness temperatures with surface parameters, although techniques exist to account for the effects in these data of surface temperature, atmosphere, and rainfall and clouds.

3. Distribution and Characteristics of Methane Emission From Wetlands

3.1 Flux Measurements

Several extensive syntheses of methane measurements and of techniques for estimating methane emission from wetlands are provided by Bartlett et al. (1990) for temperate, subtropical and tropical wetlands, and by Harriss et al. (1993) for northern high-latitude wetlands. These works were integrated and expanded in Bartlett and Harriss (1993). Refer to those publications for a comprehensive discussion of the measurements.

Methane emissions from natural wetlands show large variability resulting from the complex suite of environmental factors that affect the production of methane via anaerobic decomposition of organic material and the factors that affect transport, consumption and release of methane to the atmosphere. Fluxes measured at field sites and from soil samples have been independently correlated with local environmental and ecological factors that include temperature (Koyama, 1963; Baker-Blocker et al., 1977; King and Wiebe, 1978; Harriss et al., 1982; Mayer, 1982; Moore and Knowles, 1987, 1990; Crill et al., 1988a; Wilson et al., 1989; Klinger et al., 1994; Bubier et al., 1995a), water table position (Svensson, 1976, 1980; Harriss et al., 1982; Svensson and Rosswall, 1984; Sebacher et al., 1986; Harriss et al., 1988b; Whalen and Reeburgh, 1988; Moore and Knowles, 1989; Morrissey and Livingston, 1992; Roulet et al., 1992a; Moore and Roulet, 1993; Klinger et al., 1994; Moore et al., 1994; Liblick et al., 1997), nutrient input and organic accumulation (Harriss and Sebacher, 1981; Svensson and Rosswall, 1984; Wilson et al., 1989; Morrissey and Livingston, 1992), substrate characteristics (Sebacher et al., 1986; Valentine et al., 1994), successional status (Moore et al., 1994; Klinger et al., 1994), vegetation characteristics and phenology (Dacey and Klug, 1979; Cicerone and Shetter, 1981; Sebacher et al., 1985; Wilson et al., 1989; Whiting and Chanton, 1992; Schimel, 1995), redox potential (Svensson and Rosswall, 1984), salinity (Bartlett et al., 1985), net primary productivity (Aselmann and Crutzen, 1989; Whiting et al., 1991; Whiting and Chanton, 1993; Cao et al., 1996; Potter, 1997), and methane oxidation (King, 1992, 1994). Most researchers concur that factors influencing fluxes are not entirely independent and that variables that serve as environmental integrators of methane production and consumption processes may be more successful predictors of fluxes (Moore et al., 1990; Whalen and Reeburgh, 1992; Bubier and Moore, 1994; Christensen et al., 1995; Reeburgh et al., 1997).

A series of large-scale interdisciplinary field campaigns designed to characterize the chemistry and dynamics of the tropical regional troposphere have provided fundamental information on the role of tropical wetland environments in the global methane budget. The ABLE 2 and CAMREX missions were carried out in Amazonian Brazil in the 1985 dry season (ABLE 2A) and the 1987 wet season (ABLE 2B) (Bartlett et al., 1988, 1990; Crill et al., 1988b; Devol et al., 1988, 1990; Harriss et al., 1988a, 1990). The TROPOZ (Tropospheric Ozone) and DECAFE (Dynamique et Chimie de l'Atmosphere en Foret Equatoriale) experiments were carried out in wet and dry seasons in Central Africa during several field seasons during 1987-1989 (Delmas et al., 1992; Fontan et al., 1992; Tathy et al., 1992). Until these campaigns, low latitude wetlands had received little attention. Furthermore, early studies in low latitudes concentrated on subtropical environments of the southeastern US characterized by very low emissions (Harriss and Sebacher, 1981; Harriss et al., 1982; Bartlett et al., 1985; Barber et al., 1988). Results from the campaigns and other studies confirmed tropical wetlands as the dominant natural source of methane. This larger role is due primarily to substantially higher emission rates measured at tropical wetland sites than the rates of more subtropical/temperate environments used as tropical proxies in early estimates.

Results from the Arctic Boundary Layer Expeditions (ABLE 3A, Alaska, summer 1988 and ABLE 3B, Canada, summer 1990) (Harriss et al., 1988a, 1994) and the Northern Wetlands Study (NOWES) in Canada in summer 1990 (Glooschenko et al., 1994), as well as additional measurements in Siberia (Christensen et al., 1995) showed a pattern of fluxes from northern wetlands lower than those initially reported by Sebacher et al. (1986) and Crill et al. (1988a) (Whalen and Reeburgh, 1988, 1990, 1992; Moore et al., 1990; Morrissey and Livingston, 1992; Ritter et al., 1992; Roulet et al., 1992a, 1993; Christensen, 1993; Edwards et al., 1994; Moore et al., 1994; Ritter et al., 1994; Roulet et al., 1994). These lower values are consistent with some of those measured in the early 1980s (Svensson, 1980; Svensson and Rosswall, 1984). This shift partially reflects full-season field measurements that captured variations around the peak summer fluxes measured earlier, as well as the inclusion of less productive high-latitude sites that may occupy substantial areas in boreal and arctic regions (Ritter et al., 1992; Dise, 1993; Christensen et al., 1995; Reeburgh et al., 1997).

Using the measurement compilation of Bartlett and Harriss (1992) as a base, Matthews (1993) summarized continental/regional wetland areas and available emission measurements in wetlands of these regions. At that time, northern high-latitude systems, which account for about half the world's wetland area, were more comprehensively covered than were tropical and subtropical habitats. In North America, this coverage was heavily weighted toward Alaskan measurements and included a suite of wetland habitats measured over complete seasonal cycles and over several years. In contrast, South American measurements, although representing both wet and dry seasons, were exclusively in environments closely associated with the Amazon River. Recently, Sippel et al. (1994) and Hamilton et al. (1995, 1996) conducted studies in the large wetland complexes of the Pantanal. Russian wetlands (e.g., the West Siberian Lowlands), accounting for ~25% of the global area, were not represented at all in CH_4 flux measurements until those reported by Panikov et al. (1993) and Christensen (1993, 1995). Observational data from African wetlands remains scanty aside from the measurements of Delmas et al. (1992), Fontan et al. (1992) and Tathy et al. (1992) for forested wetlands and may remain so because of obstacles to field campaigns in these African environments (i.e., political turmoil). Methane flux measurements in Asian wetlands are still absent from the published literature.

3.1.1 Tropical Measurements

Most tropical studies have been carried out in Amazonian riverine habitats - flooded forests, floating grass mats, and lakes and channels. Bartlett et al. (1990) concluded that wet- and dry-season methane fluxes from Amazon floodplain environments may be relatively constant, but added the cautionary note that emissions during transition periods are not yet measured and may be higher. In general, methane fluxes from open water are lower and less variable than those from flooded forests and floating mats. The work of Wassmann et al. (1992) suggests differences in the seasonal pattern of peak fluxes from open water and several vegetated environments. Fluxes are similar during wet (Bartlett et al., 1990; Devol et al., 1990) and dry seasons (Bartlett et al., 1988; Devol et al., 1988) partially due to very high variability. Although there are substantial seasonal changes in inundated areas of tropical riverine systems associated with the Amazon (Melack et al., 1994; Hess et al., 1995), these habitats are not characterized by the large seasonal pulses of organic inputs from litterfall or temperature-regulated pulses of microbial activity found in higher latitudes. However, episodic events can play a significant role in seasonal emissions in the tropics and elsewhere (Table 2). Field techniques designed to measure separately the direct and ebullitive contributions to methane fluxes in tropical riverine and lake environments, as well as calculations

Table 2. Contribution of episodic events to seasonal methane emission from a series of wetland habitats.

Wetland Habitat	Mechanism/Magnitude
[1] Subarctic boreal fens	degassing pulse with lowered water table after 3 weeks of low rainfall; accounted for 18-65% of seasonal emission, depending upon habitat
[2] Temperate freshwater swamp	(direct measurement of ebullient flux) ebullition: observed in 19% of measurements, accounted for 34% of the seasonal emission
[3] Amazon floodplain	ebullition loss: 73% of emission in rising-water season, 59% of emission in low-water season
[4] Amazon lake (Lago Calado)	(direct measurement of diffusive and ebullitive flux) ebullition loss: 70% of flux from open-water lake areas
[5] Amazon floodplain	(direct measurement of diffusive and ebullient flux) ebullition loss: 49% of open-water flux, 54% of flooded-forest flux, 64% of grass-mat flux
[6] Amazon floodplain	ebullition loss: 80% of open-water flux, 91% of flooded-forest flux, 67% of floating grass-mats flux, 80% of total flux from Varzea
[7] Tropical lake (Gatun Lake)	(two techniques for direct measurement of ebullient flux) ebullition loss: 98% of total flux

[1] Moore et al. (1990); [2] Wilson et al. (1989); [3] Devol et al. (1988, 1990); [4] Crill et al. (1988a); [5] Bartlett et al., 1988); [6] Wassmann et al. (1992); [7] Keller and Stallard (1994).

of the role of bubbling in overall fluxes, confirm that episodic ebullition may commonly account for 20-75% or more of the total seasonal emission of methane in these environments further complicating measurement and modeling of fluxes from these dynamic environments (Bartlett et al., 1988, 1990; Moore et al., 1990; Wilson et al., 1989; Devol et al., 1988, 1990; Crill et al., 1988a,b; Wilson et al., 1989; Keller, 1990; Wassmann et al., 1992; Keller and Stallard, 1994). The relative role of bubbling apparently varies with ecosystem; ebullient fractions increase from open water to grass mats and flooded forest. Furthermore, bubbling events appear to be more pronounced during periods of falling and low water and in shallow lake waters.

3.1.2 Subtropical Measurements

Few measurements are available for subtropical wetlands, and are confined to the southeastern US (Virginia, South Carolina, Georgia and Florida). Wilson et al. (1989) demonstrated that seasonal trends in methane flux from the Newport News Swamp in Virginia were strongly correlated with temperature best represented by a step function. They suggest pulses of organic substrate inputs as the likely driver for the series of emission peaks observed during the year. The spring peak reflects mineralization of labile organic matter accumulated during the winter followed by temperature-triggered decomposition to substrates for methanogenesis while summer and autumn peaks are related to root exudates and litter input. The remaining subtropical measurements show considerably smaller methane fluxes from low latitude swamps. Until ~1990, the studies of Harriss and Sebacher (1981), Harriss et al. (1982, 1988b) were the only published low latitude measurements to serve as proxies for tropical wetlands.

3.1.3 Temperate Measurements

Early methane flux measurements in temperate and low boreal regions suggested these wetlands as extremely productive environments. For example, Harriss et al. (1985) and Baker-Blocker et al. (1977) showed methane fluxes in Minnesota and Michigan in the range of 200 to ~600 mg CH_4 m^{-2} d^{-1} in summer and fall. High fluxes measured in diverse wetlands in Minnesota (increasing from forested fens and bogs, to nonforested bogs and sedge meadows) were the ecosystem fluxes used to represent boreal wetlands by Matthews and Fung (1987). Later studies at Minnesota sites (Crill et al., 1988a) and a New Hampshire site (Frolking and Crill, 1994) confirm high fluxes from open bogs, circumneutral fens, and a poor fen similar to results obtained in Alaskan alpine fens (Sebacher et al., 1986). For example, Frolking and Crill (1994) reported monthly mean fluxes ranging from 21 mg CH_4 m^{-2} d^{-1} in February, 1992 to 649 mg m^{-2} d^{-1} in July, 1991. Annual totals were ~69 g CH_4 m^{-2} in both years although timing and rapidity of onset varied between the years . Finally, Dise (1992) reported that winter methane fluxes from Minnesota peatlands may account for up to 20% of the annual emission from these environments, highlighting the importance of acquiring measurements that represent all seasons.

3.1.4 Boreal and Arctic Measurements

Whalen and Reeburgh (1988) measured year-round methane fluxes at a series of permanent sites in a subarctic muskeg and along a pond margin in Alaska. These tussock and carex sites, chosen as representative of arctic tussock tundra and wet meadow tundra in the region, showed complex seasonal emission patterns. For example, although situated in similar climatic regimes, tussock sites showed positive fluxes from July through October with highest values in July-August while the carex sites showed positive fluxes from June through December peaking in August.

The first reports from the Hudson Bay Lowlands (HBL) revealed overall lower flux rates for these low boreal habitats than previously measured (Hamilton et al., 1994; Roulet et al., 1992a). Ponds (fen and beaver) exhibited fluxes in the upper range of HBL wetlands while bogs and fens averaged fluxes of 13 and 3 mg CH_4 m^{-2} d^{-1}, respectively, over the season from May to October. Individual sites within these wetland types periodically exhibited larger emission rates, e.g., a thicket swamp with emissions of 40-60 mg CH_4 m^{-2} d^{-1} in May and June, rising to 120-160 mg m^{-2} d^{-1} in July and remaining between 60-120 mg m^{-2} d^{-1} through August (Roulet et al., 1992a). Furthermore, Moore et al. (1990) found that episodic degassing pulses associated with lowered water tables following several weeks of reduced precipitation could account for ~20-65% of the seasonal emission of methane from subarctic boreal fens in Canada (Table 2).

The dry upland tundra and large lakes measured by Bartlett et al. (1992) during the July-early August period of ABLE 3A showed low summer fluxes (mean 2-4 mg CH_4 m^{-2} d^{-1}), while the smaller lake, lake vegetation and wet meadow tundra exhibited mean values of 77, 89, and 144 mg CH_4 m^{-2} d^{-1}, respectively. These chamber measurements were in reasonable agreement with eddy correlation and aircraft measurements during the same summer period. For example, Ritter et al. (1992) reported a mean of 51 mg m^{-2} d^{-1} for the tundra environments from aircraft measurements while the eddy-correlation measurement means of Fan et al. (1992) were as follows: 11 ± 3 mg m^{-2} d^{-1} for dry tundra, 29 ± 3 mg m^{-2} d^{-1} for wet tundra, and 57 ± 6 mg m^{-2} d^{-1} for lakes, giving an area-weighted regional mean of 25 ± 1 mg m^{-2} d^{-1}. Closer agreement among these measurement techniques was obtained in a similar suite of measurements taken during ABLE 3B/NOWES expeditions in 1990 although overall lower fluxes were reported. For example, Moore et al. (1994) reported chamber flux measurements for a series of wetland environments including recently emerged coastal marsh, coastal fen, tamarack fen, and interior fen (<2 g CH_4 m^{-2} for the season), 2-5 g CH_4 m^{-2} over the season from shallow ponds and pools, and 2-17 g CH_4 m^{-2} over the season for degrading peats. Hamilton et al. (1994) reported large fluxes from ponds (110-118 mg CH_4 m^{-2} d^{-1}) which covered only 8-12% of the area but contributed 30% to the methane flux in the study area. Eddy correlation measurements of Edwards et al. (1994) show a mean for all environments of 16 mg CH_4 m^{-2} d^{-1}, equal to enclosure measurements extrapolated for the region by Roulet et al. (1994).

High boreal methane fluxes taken in the Northwest Territories during the warm and dry summer of 1995 ranged from -1.3 to 1144 mg CH_4 m^{-2} d^{-1}, with a mean of 77 mg CH_4 m^{-2} d^{-1} (Liblick et al. (1997). A poor fen and collapsed bog exhibited the highest seasonal means (99-210 mg CH_4 m^{-2} d^{-1}), followed by open rich graminoid fen (47-81 CH_4 m^{-2} d^{-1}); lowest positive fluxes were observed at shrub fens (0.5-23 mg CH_4 m^{-2} d^{-1}) while woody bogs consumed methane. The overall range of fluxes reported by Liblick et al. (1997) is similar to those observed in similar environments elsewhere in Canada (Bubier et al., 1995a), although open fen emissions are substantially lower, perhaps because of the lower water table in the dry summer of 1995 in the Northwest Territories. Panikov et al. (1993) undertook several spot measurements of Siberian wetlands in the summer of 1990 which exhibited extreme variability perhaps due, in part, to the measurement technique. Christensen et al. (1995) reported the first comprehensive suite of methane flux measurements from the Siberian Lowlands, taken on a transect extending from the European to the Siberian arctic in summer of 1994. Mesic tundra sites averaged fluxes of 2.3±0.7 mg CH_4 m^{-2} d^{-1}, and wetland sites averaged 46.8±5.9 mg CH_4 m^{-2} d^{-1}; the mesic fluxes were lower than similar environments in Canada while fluxes from the high-latitude sites between 67˚-77˚N were higher than those from similar Canadian sites at lower latitudes.

Inclusion of the Siberian wetlands closed the last major gap in methane flux measurements in high-latitude environments, confirming them as generally similar to those measured in Canada and Alaska.

3.2 Regional and Global Emission Estimates

Although there is general agreement concerning the global area and distribution of wetlands, uncertainties remain as to the dynamics of wetland areas and methane production. Aselmann and Crutzen (1989) estimated total methane emission from natural wetlands to be 80 Tg with a range of 40-160 Tg, similar to the 110 Tg estimate of Matthews and Fung (1987) (Table 3). However, the relative contribution of high- and low-latitude ecosystems to the total emission was reversed in these two early studies. The high daily fluxes and emission periods of 100 or 150 days applied to boreal wetlands by Matthews and Fung (1987) resulted in about 60% of the total emission confined to the region from 50˚-70˚N; these large high-latitude emissions were later assessed to be inconsistent with the atmospheric measurements of methane concentrations and their seasonal cycles (Fung et al., 1991). Tropical/subtropical emission periods of 180 days together with lower flux rates for these low-latitude wetlands (area-weighted mean of swamps = ~100 mg m^{-2} d^{-1}) resulted in about 30% of the total wetland area in the low latitudes contributing about 25% of the total annual emission in the Matthews and Fung (1987) study. Aselmann and Crutzen (1989) assumed ~20% higher daily flux rates for the swamps and marshes predominating in the low latitudes along with emission periods of more than 250 days, resulting in a total emission largely concentrated in the tropics. Boreal and polar wetlands, with production periods averaging almost

Table 3. Regional wetland areas and associated methane emissions from studies published between 1983 and 1997.

Tropical		Temperate		Boreal/Arctic		Global		
Area $10^{12}m^2$	Emission Tg	Area $10^{12}m^2$	Emission Tg	Area $10^{12}m^2$	Emission Tg	Area $10^{12}m^2$	Emission Tg	Reference & Comments
-	90	(included in boreal)		-	66	-	156	Khalil & Rasmussen (1983)
-	-	-	-	4.5-9.0	45-106	-	-	Sebacher et al. (1986): peatlands
-	38±17	-	-	-	-	-	47±22	Seiler & Conrad (1987)
2.0	34	0.6	12	2.7	65	5.3	111	Matthews & Fung (1987)
0.1-0.5	3-17	-	-	-	-	-	-	Bartlett et al. (1988): Amazon floodplain
-	-	-	-	-	72	-	-	Crill et al. (1988a)
-	8-13	-	-	-	-	-	-	Devol et al. (1988): Amazon floodplain
2.1	45	1.1	11	2.4	25	5.7	80	Aselmann & Crutzen (1989)
2.0	55	0.6	17	2.7	39	5.3	111	Bartlett et al. (1990)
0.1	5	-	-	-	-	-	-	Devol et al. (1990): Amazon floodplain
-	-	-	-	1.5	14-19	-	-	Moore et al. (1990): fens
2.0	71	0.6	12	2.7	32	5.3	115	Fung et al. (1991)
0.1	2-3	-	-	-	-	-	-	Tathy et al. (1991): Congo Basin
-	-	-	-	7.3	44	-	-	Ritter et al. (1992): tundra
-	-	-	-	7.3	14-42 (1987)	-	-	Whalen & Reeburgh (1992): tundra
-	-	-	-	7.3	26-78 (1988)	-	-	
-	-	-	-	7.3	24-67 (1989)	-	-	
-	-	-	-	7.3	69-135 (1990)	-	-	
2.0	66	0.6	5	2.7	34	5.3	105	Bartlett & Harriss (1992)
				0.3	0.5			Roulet et al (1994): Hudson Bay Lowland
-	-	-	-	-	20±13	-	-	Christensen et al. (1996): tundra
2.0	55.2	0.6	13.8	2.7	21.8	5.3	92	Cao et al. (1996): process model
-	-	-	-	7.3	5.5-5.8	-	-	Reeburgh et al. (1997): dry tundra
-	100	-	87	-	45		232±27	Hein et al. (1997): inverse model

six months and area-weighted daily flux rates about one-quarter those assumed by Matthews and Fung (1987), played a smaller role in the emission of methane, contributing about one-third of the annual emission. The large sensitivity of emission estimates to the assumed length of methane-production seasons highlights the crucial importance of improving information on seasonal as well as interannual variations in areas and methane-production conditions for wetland ecosystems.

Bartlett et al. (1990) estimated the global methane emission from natural wetlands using areas, ecosystem classes and inundation periods of Matthews and Fung (1987) combined with updated fluxes for major ecosystems based on measurements from the Amazon Boundary Layer Experiment campaigns in 1985 (dry season) and 1987 (wet season) and new measurements from northern wetlands. The re-evaluated fluxes were higher than those of Matthews and Fung (1987) for tropical/subtropical swamps; alluvial formations were also recognized to be higher methane emitters with a flux of 160 mg m^{-2} d^{-1} in contrast to 30 mg m^{-2} d^{-1} assumed by Matthews and Fung (1987). Fluxes for boreal habitats from more comprehensive measurements were also lower, equal to about 50-75% of those used by Matthews and Fung (1987). In the estimate of Bartlett et al. (1990), tropical/subtropical ecosystems contributed about two-thirds to the total emission of methane from wetlands similar to the pattern indicated by Khalil and Rasmussen (1983) using scarce information, and Aselmann and Crutzen (1989), later confirmed in Fung et al.'s (1991) model evaluation of seasonal and spatial emissions using atmospheric CH_4 measurements as validation (Table 3). However, dominance of the low-latitude source in the work of Bartlett et al. (1990) and Fung et al. (1991) is a function of higher daily flux rates for tropical wetland ecosystems based on tropical measurements whereas the relative dominance of the tropics/subtropics in the analysis of Aselmann and Crutzen (1989) resulted from the combined effects of larger tropical wetland areas, moderately higher daily flux rates and substantially longer production seasons for these low-latitude wetlands.

Wetland areas and their geographic distribution contribute little to variations among the global estimates shown in Table 3 since the wetland data bases commonly used in these estimates are very similar. Differences among the emission studies reflect differing assumptions about the duration of methane productive seasons as well as incorporation of methane fluxes from the expanding suite of field measurements. While estimates of annual methane emission from wetlands are converging around 100 Tg, with about two-thirds emanating from the low latitudes, the very close agreement apparent in table 3 stems in part from reliance on the same inundation periods and areas in several of the studies.

Whalen and Reeburgh (1992) estimated annual tundra emissions for 1987-1990 by extrapolating mean fluxes measured in a series of habitats for each of the four years. This range of tundra estimates encompasses most of the boreal/arctic values in Table 3, which represent the full complement of northern wetland ecosystems. The tundra area of 7.3 x $10^{12}$$m^2$ used in this study is ~3 times the boreal/arctic wetland area suggested by most others. However, the measurements of Whalen and Reeburgh (1992) and others suggest that substantial portions of drier tundra may emit methane at low rates. These drier areas are not typically included in estimates although Ritter et al. (1992) suggested that regional emission estimates from ABLE 2A were an upper limit partially because the sampled areas were likely biased toward particularly productive habitats. Several recent estimates of tundra methane fluxes suggest emissions substantially lower than the 25-35 Tg commonly estimated (Table 3) while the inverse modeling of Hein et al. (1997) estimates extremely large overall emissions totaling 232 ±27 Tg which is inconsistent with modeling studies (Fung et al., 1991).

4. Modeling Wetlands and Their Methane Emissions

As noted above, the length of productive seasons as well as seasonal and interannual variations in extent of inundation remain major uncertainties in understanding the role of wetlands in the global methane cycle. Furthermore, data-based emission estimates have assumed constant daily fluxes that vary only with ecosystem type. Early efforts to introduce seasonally varying flux rates observed in the field incorporated temperature-flux relationships for northern ecosystems (Fung et al., 1991). However, while this approach provided reasonable emission patterns on a seasonal basis, other processes such as seasonal water-table variations or substrate input were not represented. While uncertainties in global methane estimates resulting from spatial and ecosystem variability have been reduced by expanding the measurement base, the most promising approach to reducing uncertainties in the seasonality of wetland areas and methane-producing inundated conditions is through integration of remote-sensing and modeling techniques.

This section is divided into three areas dealing chronologically with modeling methane emissions and wetlands: (1) early hybrid techniques of extrapolation and modeling of methane emissions from wetlands, (2) ecological process modeling of methane emissions from wetlands, and (3) modeling the distribution of wetlands.

4.1 Hybrid Extrapolation/Modeling of Methane Emissions

Early efforts to estimate emissions employed the simple approach of multiplying one or a few flux measurements of methane to wetland areas, assuming some hydroperiod. For example, Matthews and Fung (1987) used global vegetation, soils, and inundation data sets to target and characterize the distribution and environmental/ecological features of wetlands. They initially assumed methane production periods as a function of latitude, and applied daily methane emission rates for various wetland ecosystems to the appropriate ecosystems identified in the data set to estimate spatial and temporal distributions of methane emissions. Later, Fung et al. (1991) used a simple model for hydroperiod based on temperature in northern wetlands and precipitation-evaporation relationships in low-latitude wetlands; daily flux rates for wetland ecosystems were estimated using Q_{10} relationships and temperature. This technique, which provided a more reasonable seasonal cycle for wetlands, was applied to the wetland data set of Matthews and Fung (1987). Aselmann and Crutzen (1989) estimated a range for methane emissions from wetlands by assuming that 2-7% of primary productivity was emitted to the atmosphere as methane; the mean total was 80 Tg with a range of 40-160 yr CH_4 y^{-1}, boreal environments contributed ~30% to the total. Later studies focused incorporating new measurements to improve ecosystem flux estimates, but followed similar techniques of extrapolation or simple modeling to globalize the measurements.

4.2 Process Modeling of Methane Production, Transport, and Emission

Very recently, researchers have initiated efforts to model methane emissions over large areas using climatic, edaphic, and biological parameters. These models are designed to simulate more accurately the seasonal cycles of methane efflux, as well as flux variations within wetland ecosystems. For example, Cao et al. (1996) modeled supply of substrate, relationships between flux and climatic/environmental controls such as temperature and soil moisture, consumption of methane, and surface methane flux. Applying the model to the data set of Matthews and Fung (1987) gave a global total emission of 92 Tg CH_4 y^{-1}, with ~22 Tg from >50˚N, ~14 Tg from temperate regions (30-50˚N/S) and ~55 Tg from the tropics ±30˚ (Table 3) These values indicate a mean of ~3.5% for NPP ultimately released as methane, in the mid-range of such estimates (Christensen et al., 1996). Walter et al.'s (1996) methane model focused on soil physics and was validated with methane flux measurements from several northern and tropical wetland sites. It has been applied globally to the wetland data set of Matthews and Fung (1987). Total emission appears to be anomalously high at >200 Tg y^{-1}. Christensen et al. (1996) modeled methane emissions from northern wetlands using steady-state seasonal NPP and heterotrophic respiration (HR) from the BIOME ecosystem model (Prentice et al., 1993), and accounting for peatland carbon storage. Methane emission is a proportion of HR with a constant of proportionality estimated from observations and varying with ecosystem. Applying the model to the same wetland data set used by Cao et al. 1996) and Walter et al. (1996), they estimate that northern wetlands emit 20 Tg CH_4 y^{-1}, generally consistent with other studies (Table 3). Recently, Potter (1997) published a 1-D methane model that includes water table and thaw depth, substrate production and decomposition, methane production and transport, and surface methane flux parameterized for a suite of tundra plant communities; the model has been validated with the seasonal tundra measurements of Whalen and Reeburgh (1992).

All the models summarized above perform reasonably well in simulating the seasonality and magnitude of methane emissions from wetlands. However, all have been applied either at single sites or to the externally-prescribed distribution of the same wetland data set so that the modeled features of methane emission encompass no impact from seasonal, interannual, or longer-term trends in the distribution of wetlands themselves. Currently, the principal barrier to development of comprehensive wetland-methane models is the difficulty of modeling the distribution of wetlands themselves, as well as their seasonal and interannual variations with climate although such capability is required in order to assess responses and feedbacks between climate change and wetlands for past and future climates.

4.3 Modeling Wetland Distribution

Parameters known to influence the distribution of wetlands include climate, topography, slope, vegetation, and soils etc. However, these parameters have not yet been used successfully to model wetland location, extent or behavior due to the complex dynamics among the variables, as well as to the very local nature of their variation and influence. Global estimates of some of these parameters are now becoming available, and efforts have recently begun to incorporate them into simulations of terrestrial hydrologic processes.

Coe (1997, 1998) reports on a global model designed to simulate mean annual terrestrial hydrologic processes including rivers, lakes, and wetlands as a linked dynamic system. The model has two main components currently operating at 5' latitude by 5' longitude resolution. The land surface component, derived from digital elevation data, determines potential surface water areas, maximum water volume within potential lakes and wetlands, and the direction in which excess water is transported across the land surface as rivers. The water volume component uses a linear reservoir model, and estimates of runoff, precipitation, and evaporation to determine the water volume available to fill potential water areas and to form rivers. These linked components dynamically simulate the transport of water across the land surface and to the oceans in the form of rivers, as well as the storage of surface water in lakes and wetlands. However, wetland simulation is poor in many regions where wetlands are common, and wetlands are arbitrarily defined as water bodies with a depth of 1 meter or less. Coe (1998) suggests that accurate wetland simulation is hampered primarily by limits imposed by the 5' resolution of the digital elevation model (DEM) used to date because many wetland complexes are composed of features too small to resolve at this resolution.

For methane studies, a linked hydrological model such as that of Coe (1998) is the most promising approach to simulating variations in wetland extent and depth on seasonal and interannual timescales. With such a hydrological model available, the importance of specific plant communities to methane emissions makes it likely that the hydrological model will be integrated with vegetation models for methane studies (Bubier et al., 1995b; Christensen et al., 1995; Potter, 1997).

5. Wetlands and Climate Change

About half of the global wetland area, and the majority of peatlands, occur in latitudes between 50˚ and 70˚N, regions expected to undergo temperature increases on the order of several degrees C during the next 100 years (Hansen et al., 1988, 1997; Gorham et al., 1991; Houghton et al., 1996). These changes may lead to (1) a lengthened thaw season and associated increase in biological activity, (2) larger areas subjected to thaw and anaerobic conditions, (3) increased net primary productivity due either to direct fertilization from increases in CO_2 concentration or to indirect temperature effects, (4) changes in above- and below-ground carbon allocation, and/or (5) changes in plant distributions and successions. Based on temperature increases alone, methane emissions would probably increase in high latitudes providing a positive feedback on the climate system. However, other factors may moderate this response. For example, nutrient limitation may restrict productivity increases and microbial adaptation to the current thermal regime may be inelastic. Available water supply in high latitudes may decline in response to increased evaporation under warmer conditions which could produce lower water tables and dry soil conditions in previously waterlogged or inundated environments, thereby increasing methane oxidation, reducing methane emissions and perhaps causing former wetlands to act as methane sinks. Seasonal precipitation is the major controller of tropical and subtropical methane emissions, affecting both area and length of inundation periods. While General Circulation Models generally predict greater precipitation for high-latitude wetland areas in the future, low-latitude regions may be subject to reduced precipitation. However, predictions of hydrologic perturbations over the next 50-100 years are highly uncertain, leaving open the question of whether current wetlands will become larger or smaller methane sources or perhaps sinks in the future. As noted above, difficulties in integrating the climatic, edaphic, and topographic underpinnings of wetland behavior indicate that very local conditions determine whether current wetland sites may expand or contract, and whether per-unit-area fluxes increase or decline.

A suite of investigators have evaluated potential changes in methane emissions from high latitude wetland ecosystems in response to predicted climate alterations using current relationships between methane flux and climate variables (Table 4). Frolking (1993) and Harriss and Frolking (1992) evaluated possible inter-annual oscillations in high latitude summer methane emission from wetlands as a function of 20th century temperature variations. Compared to baseline long-term summer averages, temperature anomalies range from about -2˚C for the coolest years to +2˚C for the warmest. Based on reconstructed summer temperature anomalies in high latitude wetland regions, and correlations between temperature and methane flux measurements in Alaska and Minnesota, they estimate that summer methane emissions from boreal wetlands during the last century have varied approximately 5 Tg around a mean of 32 Tg. This result suggests that wetland emissions are moderately sensitive to the magnitude of temperature variations that might be expected in the

Table 4. Methane emission and climate change (adapted from Matthews (1993) and Öquist et al. (1996).

Description	Methane-Emission Response
[1] Relationship between regional North Slope (Alaska) tundra emissions and temperature; simulated changes in water status via changes in vegetation distributions; extrapolation using 1987-1989 measurements	local: 4-fold increase with 4˚C summer soil temperature rise; regional: 4-5-fold increase under 4˚C warmer and wetter conditions 2-fold increase under 4˚C warmer and drier conditions large sensitivity to warming
[2] Sensitivity of high latitude emissions to historical summer temperature variations; no evaluation of water status; temperature-flux correlations and regional 20th century temperature anomalies used to model historical flux	± 2˚C anomalies gave ±5 Tg variation around mean annual emission of ~30 Tg; suggests that 3-5˚C rise could double emissions: moderate sensitivity to early warming
[3] Four-year time series of flux measurements at fixed Alaskan tundra sites extrapolated to estimate interannual variations in high-latitude tundra emissions	4-fold emission variation over four years: 14-42 Tg (1987, driest), 26-78 Tg (1988), 24-67 Tg (1989), 69-135 Tg (1990, wettest): large sensitivity to combined temperature and water effects
[4] Measurements of methane emission and related environmental factors in low boreal Canadian fens; water-table position predicted with hydrologic/thermal model for peatlands	15% emission increase with 2˚C elevation in soil temperature; moderate sensitivity to warming, large sensitivity to water status
[5] Measurements of methane emission and temperature from drained 20 cm drop in water table reduced flux to zero: boreal wetlands in Finland	4 cm decline in water table reduced methane flux by 80%; large sensitivity to water status
[6] Measurements of methane emission and water table in drained boreal wetlands in Canada	100% reduction of emission with 10 cm decline in water table; >10 cm water table drop changed wetland to small methane sink: large sensitivity to water status
[7] Sensitivity study of modeled methane emission to temperature increase	2˚ T increase increased emission by 36%, 29%, and 12% in northern, temperate and tropical wetlands; large sensitivity to temperature in northern environments

[1] Livingston and Morrissey (1991); [2] Frolking (1993), Harriss and Frolking (1992); [3] Whalen and Reeburgh (1992); [4] Roulet et al. (1992c); [5] Martikainen et al. (1992); [6] Roulet et al. (1993); [7] Cao et al. (1996).

early stages of warming predicted for the next century. Frolking (1993) further suggests that a 3-5˚C temperature rise, with no change in water status, might increase boreal emissions to more than twice their current estimated value. Livingston and Morrissey (1991) evaluated the sensitivity of regional North Slope (Alaska) methane emissions to potential changes in both temperature and water status. *In situ* flux measurements show a three-fold increase in response to the ~5˚C mid-summer soil temperature elevation observed in the study area between the 1987 and 1989 field seasons. Extrapolation to the North Slope region suggests a potential four-to-five-fold increase in emission under conditions wetter than those of 1987 and a doubling of methane emission with a 4˚C elevation even under conditions moderately drier than 1987. Based on methane measurements at a broad suite of tundra sites in Alaska, Whalen and Reeburgh (1992) estimated annual tundra emissions for 1987-1990 based on mean emission values for tundra habitats measured over the period. Interannual fluxes varied substantially over the period which encompassed consistent summer temperature anomalies of +2˚C and precipitation variations ranging from ~60% (1987-1989) to 190% (1990) of long-term averages. Estimates of total tundra emissions vary by a factor of four, from 14-42 Tg CH_4 in the driest year (1987) to 69-135 Tg in 1990, the anomalously wet year. These latter two analyses based on field measurements indicate potentially large sensitivity of high latitude methane emissions to combined effects of temperature and precipitation changes. The analyses of Roulet et al. (1992b) on the sensitivity of methane emissions to temperature and to water-table variations in Canadian fens indicate a moderate dependence of the emissions on temperature but a very strong dependence of emission on water table depth. Their modeling study suggests an emission increase of ~15% with a 2˚C elevation in temperature at 10 cm soil depth but ~75-80% declines in emissions from floating and non-floating fens following a 14 cm drop in water table.

In the Northwest Territories (Liblick et al. (1997), as well as in NOWES sites (Moore et al., 1994), largest methane emissions were associated with degrading and collapsing peats. Based on this evidence, Liblick et al. (1997) hypothesize that increased permafrost melting will initially increase boreal methane emissions due to formation of collapse scars, but that such increases will eventually reverse with lowered water tables and associated increases in methane oxidation. Similarly, Hamilton et al. (1994) suggest that high-latitude warming may increase landscape ratios of ponds (with high fluxes) to vegetated areas (lower fluxes), increasing overall fluxes.

Christensen and Cox (1995) developed a model of permafrost thermodynamics and methane emission and drove it with current and $2xCO_2$ climates from the UK Meteorological Office GCM, as well as with North Slope field measurements. Simulated methane emissions in the $2xCO_2$ experiment increased due to slightly warmer temperatures. However, the dominant cause of increased emissions was from a 42% increase in mean thaw depth as a result of deeper maximum thaws and a longer thaw season. This result, along with the measurements of high-latitude peatlands, illustrate the sensitivity of emissions to the combined effect of temperature and moisture impacts of changing climates.

A primary determinant of high latitude wetland responses to climate change lies in the extent to which anaerobic conditions are maintained under circumstances of reduced moisture availability. Seasonal, areal and vertical components of methane production and consumption activities will likely adjust differently to moisture changes.

6. Summary

6.1 Area, Distribution, and Seasonality of Wetlands and Emissions

Presently-available information on the distribution of wetlands exceeds large-scale information on methane production, oxidation and emission characteristics. Independent data sources generally agree on latitudinal and environmental profiles of wetlands. A comprehensive suite of methane flux measurements conducted in a broad array of geographically and ecologically diverse ecosystems has characterized large-scale features of the role of natural wetlands in the global methane cycle. Model studies including photochemical and transport processes, as well as regional emissions estimates derived from tower- and aircraft-base eddy-correlation techniques, suggest patterns consistent with the ground-based measurements.

Tropical and subtropical wetlands, which account for about one-third of the global wetland area, likely contribute ~50-75% to the annual emission of methane from natural wetlands. Precipitation-driven inundation periods may last from a few to 12 months a year in these environments. More than half the world's wetlands occur in boreal and arctic habitats north of 50˚N. As in the tropical riverine wetlands, many of these environments are characterized by complex landscapes composed of herbaceous and open-water features with distinctive methane emissions. At present boreal methane emissions, telescoped into a few months of the year during thaw seasons, probably contribute about one-third of the world's total wetland emissions.

The largest uncertainties in the role of wetlands and their methane emission in the global methane cycle are variations in inundation periods, seasonal changes in wetland habitat areas, interannual variations in inundation extent. these uncertainties in wetlands themselves translate into uncertainties in emissions. The dependence on climate of wetland variations and emissions remains the major uncertainty. Remote sensing and model development are contributing to reducing these uncertainties in seasonal and interannual variations. Remotely-sensed data can provide information on seasonal and interannual expansions and contractions of wetlands, and may allow simple parameterizations of wetlands in GCMs and/or biogeochemical models.

6.2 Flux Measurements

Methane fluxes have been measured in all major wetlands. the recent measurements in the Siberian lowlands and the South American Pantanal closed the last gaps in ecosystem coverage of methane emissions although seasonal variations in the former should be better quantified . The seasonality of methane emissions for most wetland habitats is well measured as are interannual variations in high-latitude fluxes. Many Amazonian environments have been measured in both wet and dry seasons although African wetlands are poorly represented by field measurements with respect to seasonal and interannual variations, and no measurements exist for herbaceous wetlands in Africa. Low-latitude Asian wetlands are not measured at all but occupy a small area globally. While sites in Manitoba and Quebec initially dominated measurements of methane emissions in Canada, field studies from the Northwest territories, which account for 25% of Canada's wetlands, have recently become available. Continued measurements in Canada confirm general patterns and levels of fluxes measured earlier in the 1990s.

Measurements of methane fluxes in natural wetlands continue to confirm that methane fluxes can vary by orders of magnitude among ecosystems at local scales, and by factors of three to four interannually in response to temperature and water-status variations. Moreover, episodic events have been shown to contribute substantially to total seasonal emissions in a broad array of wetlands accounting for 20-75% of seasonal methane emissions in tropical environments; similar fractions due to degassing pulses associated with lowered water tables have been observed in Canadian wetlands. Given the relatively comprehensive coverage of wetland habitats with respect to flux measurements, researchers are now focusing more on quantifying complex interactions among dynamic environmental variables and their influence on fluxes. Variables that serve as environmental integrators of production and consumption processes remain the most promising predictors of methane fluxes.

6.3 Regional and Global Emission Estimates

Tropical and subtropical wetlands, which account for about one-third of the global wetland area, likely contribute ~50-75% to the annual emission of methane from natural wetlands. Precipitation-driven inundation periods are highly variable and may last from a few to 12 months a year in these environments. More than half the world's wetlands occur in boreal and arctic habitats north of 50^{o}N. As in the tropical riverine wetlands, many of these environments are characterized by complex landscapes composed of herbaceous and open-water features with distinctive methane emissions. At present boreal methane emissions, telescoped into a few months of the year during thaw seasons, probably contribute about one-third of the world's total wetland emissions. However, their response to climate changes predicted for the next century is highly uncertain. Depending on local interactions among temperature, water status, nutrients, microbial populations etc., boreal/ arctic ecosystems may become larger or smaller methane sources, or methane sinks.

6.4 Modeling Emissions, Wetlands and Climate Change

Uncertainties in the response of methane emission from wetlands to climate changes predicted for the next century remain large. Depending on very local interactions among temperature, water status, nutrients, microbial populations etc., current wetlands may become larger or smaller methane sources, or methane sinks. Researchers have used interannual variations in climate during field studies as proxies to predict likely scenarios of climate change impacts on emissions. However, modeling and field studies do not indicate any clear trends in emissions under changed climates primarily because few studies include the combined effects and interactions of hydrological and thermal parameters. Direct effects of increasing temperature, as well as indirect effects of increased thaw season and depth, would increase CH_4 emissions if local hydrological regimes remained constant. However, reduction in precipitation or lowering of water tables in present wetlands would likely reduce emissions under constant or increasing temperatures.

Recently-developed methane-emission models perform reasonably well when applied to independently-defined wetland distributions. However, simulating the response of wetlands and their methane emissions to climate change requires linked hydrological and ecosystem models preferably integrated into GCMs, i.e., modeling the distribution and variations of wetlands as well as their methane emissions. Modeling wetlands directly is a more difficult problem because of extremely local influences (e.g., topography) on wetland distribution and area. However, simulation of interactions among terrestrial methane sources, atmospheric composition, and climate hinges upon such integrated modeling.

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